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NAVAL POSTGRADUATE SCHOOL
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THESIS

INITIAL DESIGN STUDY OF EXISTING
FLIGHT CONTROL SYSTEM OF RPH
AND
FEASIBILITY STUDY OF IMPLEMENTING
HHC ON THE SH-60B

by

Charles David Webb

September 1990

Thesis Advisor: E. Roberts Wood

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Initial Design Study of Existing
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HHC on the SH-60B

by

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ABSTRACT

The paper reports on two subjects, first the initial design study of a Remotely Piloted Helicopter's flight control system and secondly a feasibility study of implementing Higher Harmonic Control on the SH-60B aircraft. Described for the former is a complete study of stiffness constants, system freeplays and power requirements needed to provide Higher Harmonic Control to the Remotely Piloted Helicopter. The later gives practical design considerations for four alternate mechanical/hydraulic designs. The Remotely Piloted Helicopter Higher Harmonic Control work is a ongoing project at the Naval Postgraduate School the SH-60B work is a initial study which is currently being evaluated at the Naval Air Test Center.

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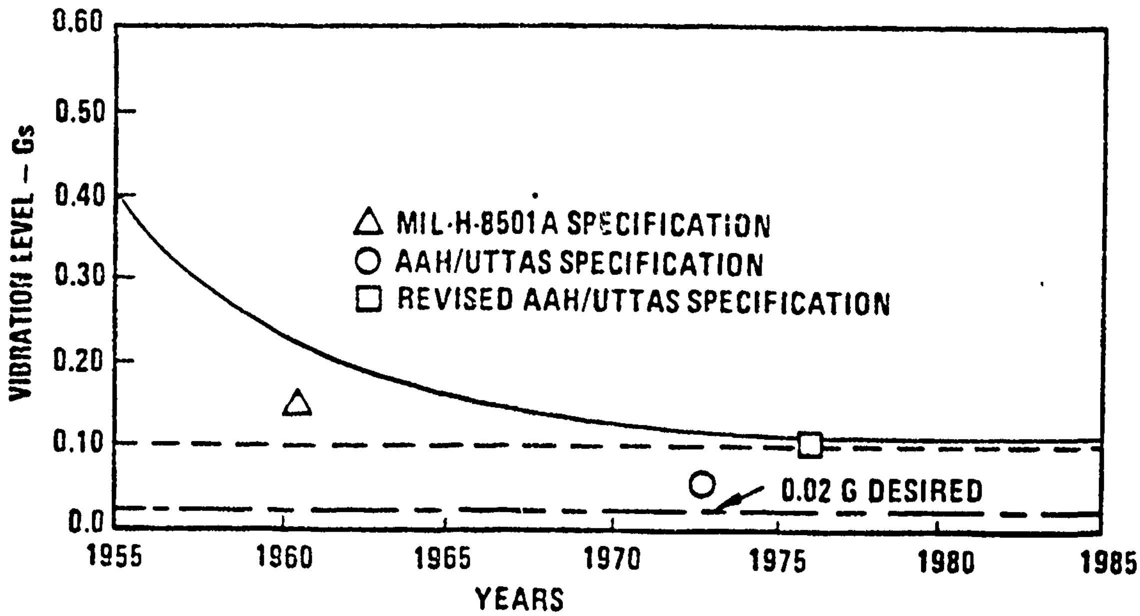
I. INTRODUCTION

Helicopter vibrations are detrimental to all components of the aircraft and crew. As can be seen in Fig. 1 the trend of helicopter crew station vibration levels has decreased over the past 30 years. Even with this noteworthy decrease in vibration levels, vibrations are still a major cause of pilot and aircrew fatigue. If compared with levels in a jet aircraft (shown by line at 0.02g), substantial reductions in vibration levels can still be achieved. Vibrations also cause fatigue of rotor, airframe components and costly damage to electronic and optical gear such as weapons tracking and sighting gear. Although there has been a significant vibration reduction in helicopters using passive devices such as isolators or absorbers a break through was needed to obtain vibration levels close to those of fixed wing aircraft.

A new means in which vibrations are controlled at their source by active means is by the use of Higher Harmonic Control (HHC). With this active system vibrations are reduced by altering aerodynamic loads on the rotor system so that the prime forces and moments which produce helicopter vibrations are reduced prior to being transmitted to the airframe. In other words; the vibrations are reduced or eliminated before they get to the airframe. To cause this reduction in vibrations the HHC system senses airframe vibrations through accelerometers. This signal is processed through an A to D converter then sent to a microcomputer which interprets the signal and sends out the appropriate signal to servo-actuators which cause high frequency feathering of the rotor blades



Trend of Helicopter Vibration Levels Since 1955
Figure 1

through the swashplate [Ref. 1].

In the previous paragraph the most popular approach to accomplish HHC is described but there are other options. HHC could also be accomplished by the use of servo flaps and other methods that use aerodynamic forces to help in the feathering of the blades. HHC has reached a point where numerical analysis, full or model scale tests in wind tunnels, and full scale flight tests have confirmed that HHC is capable of reducing vibrations, and also yield a possible increase in performance. See References 1 through 5.

II. SCOPE

The Department of Aeronautics and Astronautics at the Naval Postgraduate School (NPS) has recently acquired a remotely-piloted helicopter (RPH) in which practical hands-on HHC research will be conducted. The RPH was acquired by LT J. G. Scott from the Pacific RPV Company. This vehicle, though not a full scale helicopter, is a good vehicle in which students will be able to do ongoing HHC research. Now that the flight test vehicle is available an operating and fully functional HHC system has to be designed, developed, installed and checked out on the RPH. Initial design and development of an HHC control system for the RPH was by Mr. Rambin and his company, Vista Controls of Ventura, California. This work combined with that of students at NPS has led to an ongoing research and acquisition process.

In addition to design and development of a radio-controlled RPH for investigating HHC, efforts are also underway to modify a Sikorsky SH-60 for HHC testing at the Naval Air Test Center (NATC). This requires a preliminary design study of the SH-60. The scope of this master's project is to cover both programs. This research effort, then, is a feasibility study of implementing HHC on a fleet airframe; the Sikorsky SH-60. This effort required a trip by the author to NATC for a visual inspection of the airframe and its control system. Second it required the research of several different HHC systems and finally required the selection of an optimal system.

III. HIGHER HARMONIC CONTROL MODIFICATIONS FOR RPH

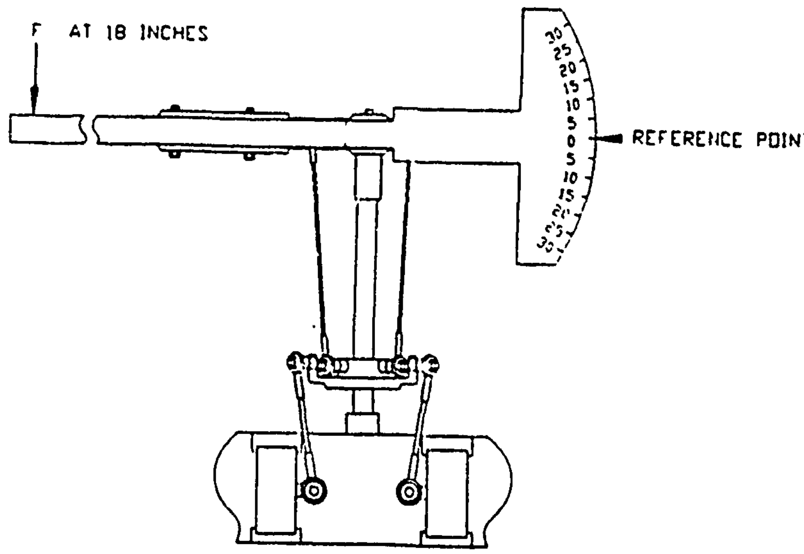
A. CONTROL SYSTEM FREEPLAY AND STIFFNESS CONSTANTS

The reasoning for measuring freeplay and stiffness constants is if the system is too flexible then output from the servos is not transmitted to the blades completely. The most extreme case is freeplay where servo motion is totally lost in being transmitted to the blades. Freeplay and flexibility also mean that more power is required for a given amount of blade motion since the stroke or travel of the actuator increases.

1. System Stiffness For Existing RPH Flight Control

The first step toward developing a flight control system for the RPH that could provide HHC actuation was to analyze the existing system. From this analysis it was then required to determine the stiffness of the proposed HHC system and to identify individual items critical to the design of a working HHC actuation system.

In this first step an initial test was run to find the total system stiffness. By starting with the total system it would be known right away if the system contained too much free play. Power was turned on so that the actuators (servos) were able to operate and all linkages were connected. The transmitter was set so that the cyclic was centered and collective was set at about mid range. With the control positions set the blade that was to be weighed was positioned in such a way that only two of four servos opposed the movement of the swashplate seen in Fig 2. By placing weights on the 18-inch cantilever arm, maximum torque was produced at the blade retention with the pitch gauge

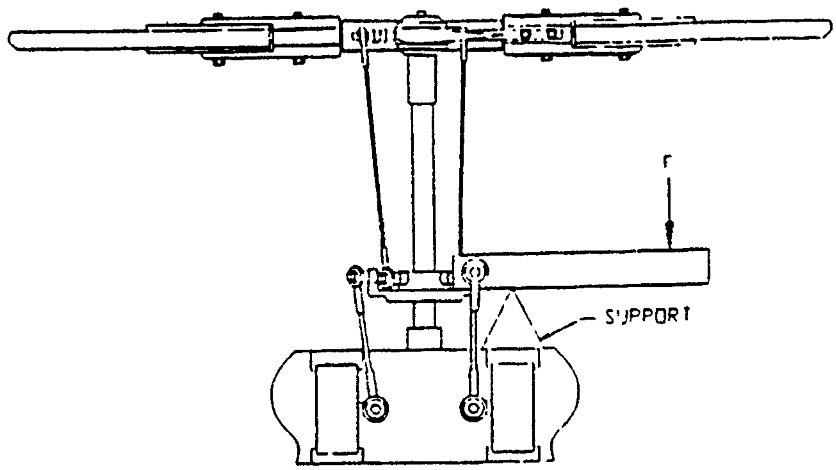


System Stiffness Test
Figure 2

in place so a displacement (twist) reading could be made. By repeating this method on all blades independently in both a positive and negative direction a good reading of system stiffness or torsional spring constant could be obtained.

2. Servo Stiffness

To calculate the servo actuators stiffness a small device was set up as can be seen in Fig 3. To accomplish this test the servo link was disconnected at the swashplate end. The linkage was fastened to a cantilever beam, which in turn was supported by a small

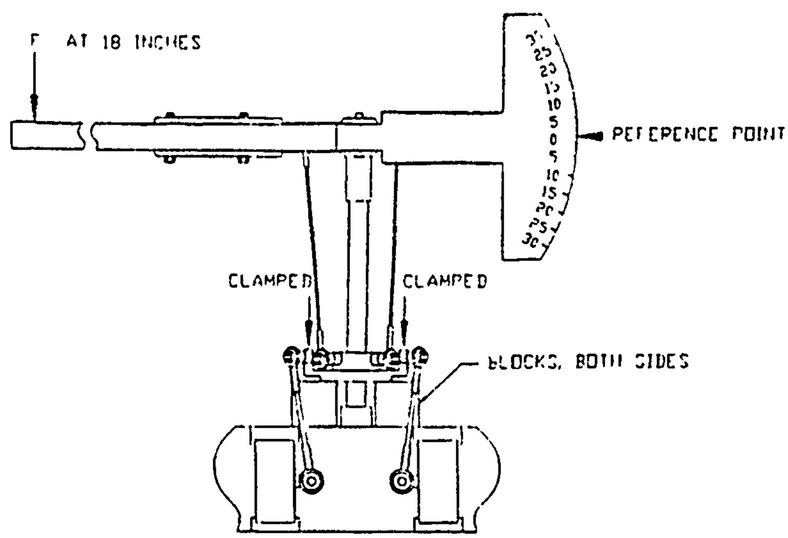


Servo Stiffness Test
Figure 3

piece of aluminum acting as a fulcrum. The fulcrum mechanism gave a 2 to 1 advantage for the force being applied. The test was run in the following manner. The transmitter and servos were turned on and the system was zeroed. Weights were then placed on the cantilever to produce a force on the servo. Linear motion of the servo link pointer was then measured against a stationary linear scale. The data obtained was then converted so that the stiffness for the servo actuator at the blade root could be obtained. It should be noted that the test device only worked in one direction. This was due to the fact that the fulcrum could only be placed atop the servo motor due to size constraints.

3. Rotating System Stiffness

The final stiffness measurement is that of the rotating system linkage consisting of the pitch links and pitch horns. To measure the stiffness of this system the rotating swashplate was required to be stationary. To accomplish this a small rig consisting of clamps and blocks was required as can be seen in Fig 4. As in the total system



Rotating System Stiffness Test
Figure 4

measurements, a cantilever beam and pitch gauge were used to create a torque at the blade grip and then measure it.

B. BLADE PROPERTIES

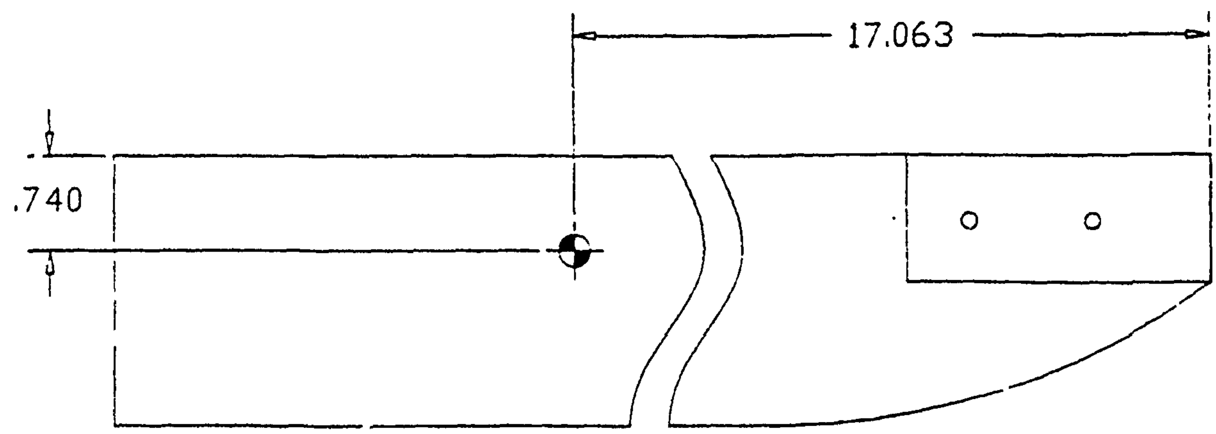
Each individual blade was measured and weighed so that its center-of-gravity could be located. The spanwise center-of-gravity was established by simply supporting the blade on a roller pin until it was balanced. The blade dimensions and average CG locations can be seen in Fig 5. Next the blade's mass moment of inertia was approximated by splitting up the blades cross section as shown in Fig 6. To do this, an assumption was made that the blade was constructed of a homogenous material. This is a good assumption since the blades are in actuality made of wood and weighted so the rotor system is balanced. Even though this assumption is made, it is felt that the approximation is valid.The following equations were used to calculate the individual section mass moments of inertia and that of the whole blade [Ref. 6].

$$J_{z_{REC}} = \frac{m}{12}(4a^2 + b^2) \qquad (1)$$

$$J_{z_{TRI}} = \frac{m}{72}(12a^2 + 3b^2) + md^2 \qquad (2)$$

$$J_{BLADE} = J_{z_{REC}} + J_{z_{TRI}} \qquad (3)$$

A blade flapping hinge stiffness was obtained by the use of the test rig used to find the earlier stiffness constants. By securing the swashplate and placing the cantilever beam along the center line of the blade grip a stiffness constant was obtained.

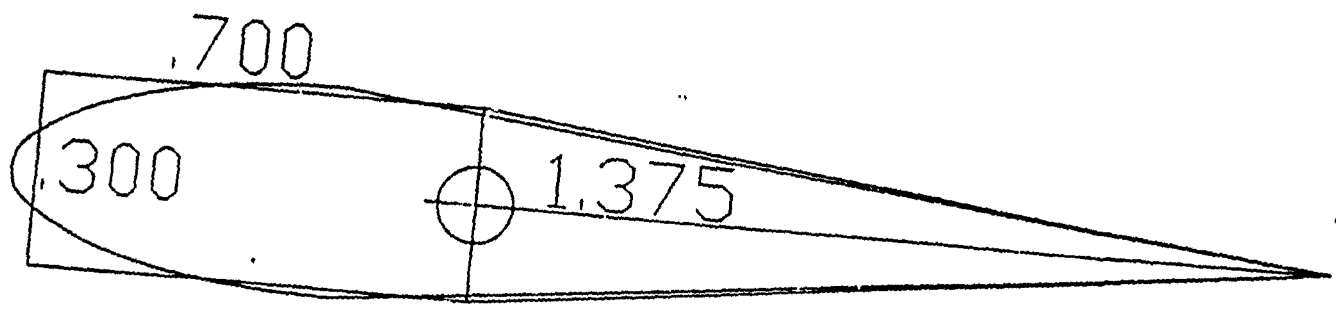


Blade Center of Gravity
Figure 5

To make measurements of the blade deflection a dial gauge was placed underneath the blade grip assembly as shown in Fig 7.

C. BLADE GRIP PROPERTIES

The blade grip is a cylinder with two flat plates fastened to it. It is used to hold the blade to the rotor head as seen in Fig 8. Since it is a rotating member a mass moment of inertia is required. To approximate the mass moment of inertia the blade grip was subdivided into parts, comprising the cylinder and plates.



Blade Cross Section
Figure 6

In this case since the material is aluminum, the assumption of homogenous material is valid. The weights and mass moments of inertia were calculated using the following equations.

$$W_{T_{cyl}} = (\pi R^2 - \pi r^2) L\rho \qquad (4)$$

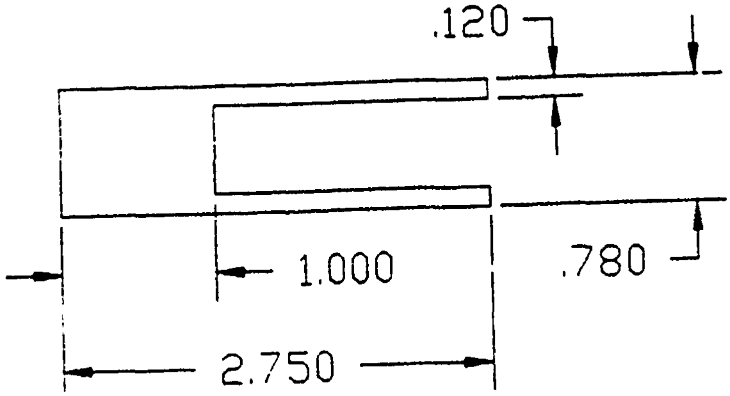
$$W_{T_{pl}} = \rho VOL \qquad (5)$$

$$J_{z_{pl}} = \frac{m}{12}(b^2 + c^2) + mx^2 \qquad (6)$$

$$J_{z_{cyl}} = \frac{m}{2}(R^2 + r^2) \qquad (7)$$

$$J_{z_{sa}} = J_{z_{cyl}} + J_{z_{pl}} \qquad (8)$$

Blade Flapping Measurements
Figure 7



BLADE GRIP
FIGURE 8

D. PITCH LINK PROPERTIES

The pitch links are in the rotating plane. An approximation of their mass moment of inertia was calculated as follows Distance from the blade axis of rotation to the pitch links was taken into account with the following equations:

$$W_{t_{LNK}} = \pi r^2 L \rho \qquad (9)$$

$$J_{s_{LNK}} = m r^2 \qquad (10)$$

E. SYSTEM PROPERTIES

With all the mass moments of inertias approximated for the rotating system, the total mass moment of the blade system could then be calculated by the following equation.

$$J_{z_{SYS}} = J_{z_{BLADE}} + J_{z_{BLADEGRIP}} + J_{z_{LINK}} \qquad (11)$$

F. POWER REQUIREMENTS

Upon completion of the mass moment of inertia calculations, an estimation of power needed to actually move these blades in the HHC mode was required. Once required actuator power was determined, a candidate actuator could be selected. To achieve maximum acceleration several variables had to be established. Since the normal operating RPM is 1100 with maximum RPM of 1300 an RPM of 1200 was chosen for power calculations. Next, the maximum pitch acceleration was calculated, based upon $\pm$ 1 degree of pitch and an HHC actuator frequency of 80 Hz. The pitch angle was taken from [Ref. 1]. To obtain a maximum angular acceleration the following equations were used.

$$\theta = A\cos(4\omega t + \phi) \qquad (12)$$

$$\omega = \frac{d\theta}{dt} = -4\Omega A\sin(4\Omega t + \phi) \qquad (13)$$

$$\alpha = \frac{d\omega}{dt} = -(4\Omega)^2 A\cos(4\Omega t + \phi) \qquad (14)$$

Where θ is the angular displacement, A is the amplitude, t is time, ϕ is the phase constant, ω is angular velocity and α is the angular acceleration. To solve for maximum acceleration an initial condition must be set. Setting ϕ equal to zero causes the maximum blade pitch angle (A) to occur at t equals zero and the maximum angular acceleration to occur at a point 180 from θ max..

Now that the maximum angular acceleration is known, the pitch torque requirement can be calculated. The maximum RMS torque required was obtained using the following equation:

$$T_{MAX} = \alpha_{MAX} J_{z_{SYSTEM}} \qquad (15)$$

IV. RESULTS

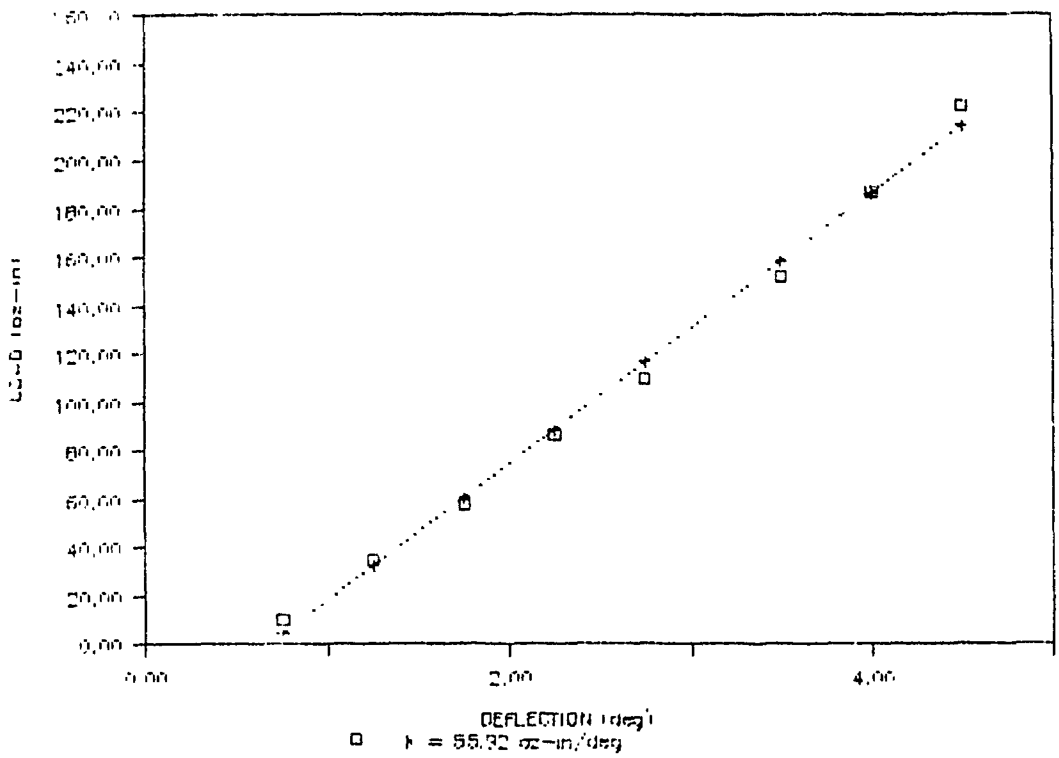
A. STIFFNESS CONSTANTS

1. Total System

As seen in Table 1, data was obtained in a positive and negative manner and for two sets of servo loadings, pitch and roll. By taking the force applied and multiplying by the moment arm the torque on the system was calculated. The calculated torque was then plotted against the blade pitch angle as seen in Fig. 9. The scope of the graph in Fig. 9 yields the total system stiffness constant of 56 oz-in/deg. And the system free play is found where the line intersects the zero load axis, 1.3 degrees. With 1.3 degrees of freeplay, the system contains too much slop and must be "tightened" if HHC is to work. If the HHC actuators have to produce much more than 1 degree of blade feathering, power required becomes too large. This will be shown in the power required section.

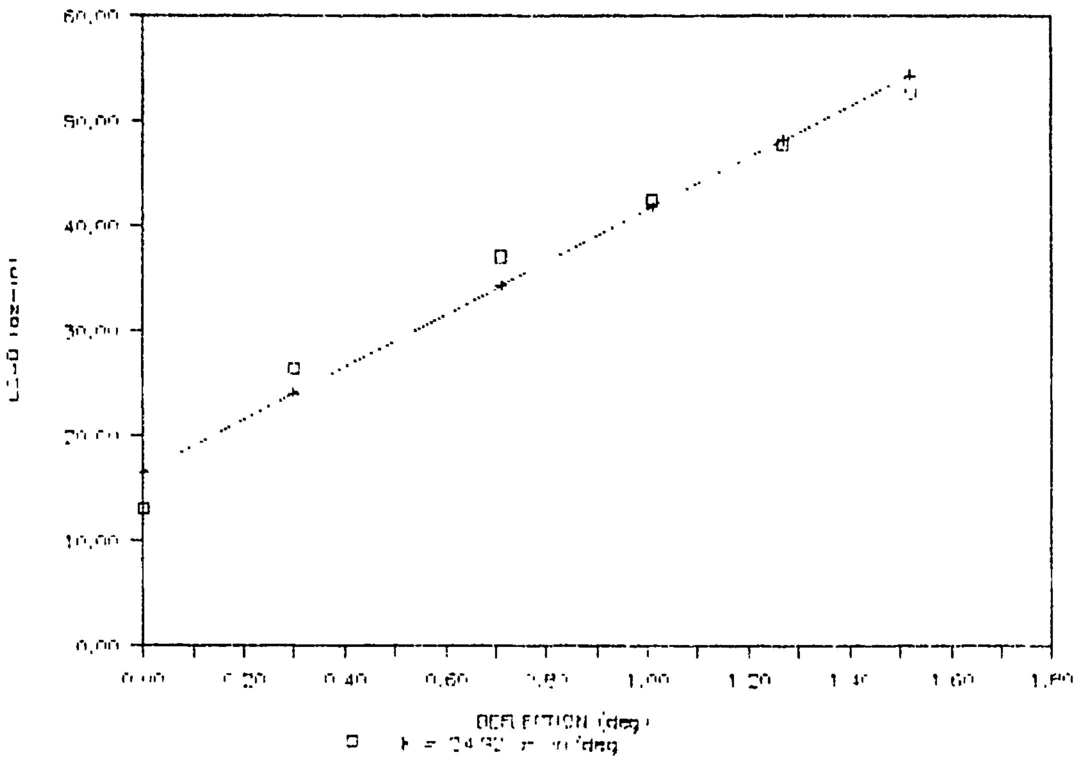
2. Servo Stiffness

For the servos, data was taken by measuring a linear displacement when an incremental load was applied to the cantilever. As seen in Table 2, data was obtained at the servo and then adjusted for blade load and deflection. To do this adjustment several parameters had to be found. First the ratio between the servo deflection and blade deflection was established as: 1.61 servo to 1 for blade. And secondly the linear to rotational deflection conversion was found to be: .296 inches to 24.2 degrees. With these conversions raw data was adjusted to the blade. The data was then plotted in Fig. 10 and



Total System Stiffness Constant
Figure 9

a stiffness coefficient of 24.9 oz-in/deg was obtained from its slope. By looking closely at this plot it is clearly seen that the servo stiffness is not linear as was initially assumed. This non-linearity can be attributed to the fact that as more load was added to the servo the servo arm began to bend and twist. Since the plot is not very reliable, an estimate of freeplay was made by observing it during loading.



Servo Stiffness Constant
Figure 10

TABLE 1. Total System Stiffness Constant Data

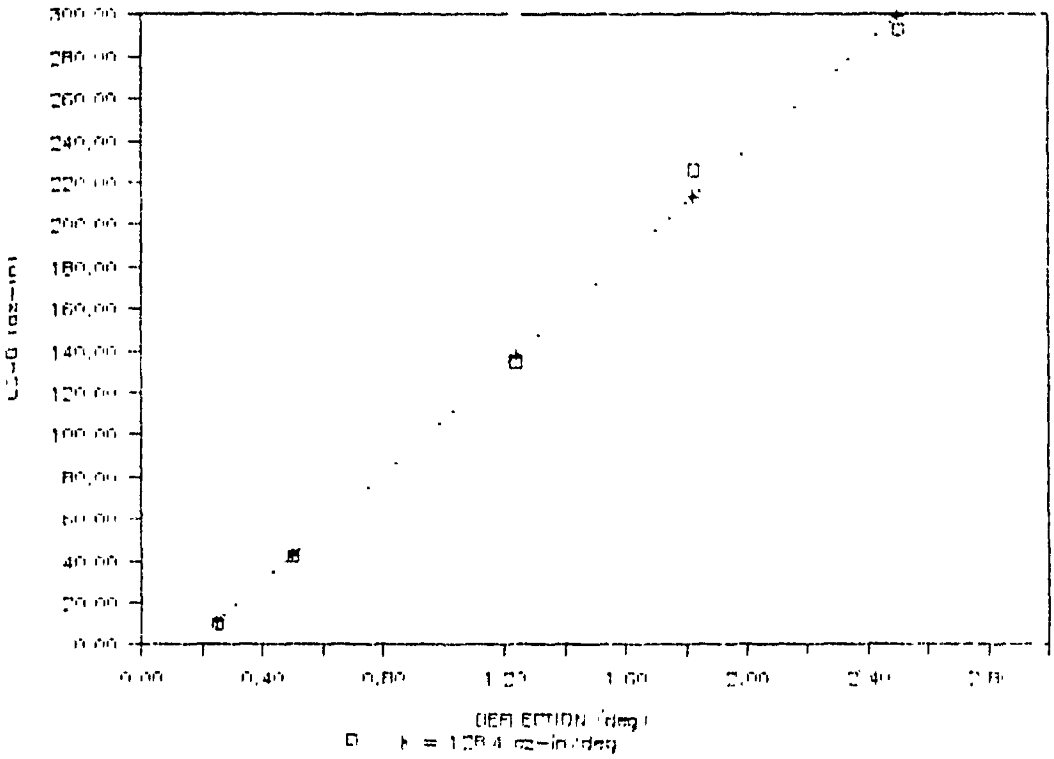
APPLIED FORCE (oz)	TORQUE (oz-in)	ROLL SERVO LOADING BLADE PITCH ANGLE (degrees)	PITCH LOADING BLADE PITCH ANGLE (degrees)
0.56	10.16	0.75	0.75
1.94	34.92	1.25	1.50
3.21	57.78	1.75	1.80
4.83	86.98	2.25	2.00
6.10	109.84	2.75	2.50
8.43	151.75	3.50	3.10
10.41	187.30	4.00	3.60
12.38	222.86	4.50	4.25
-0.56	-10.16	-0.75	-0.75
-1.94	-34.92	-1.25	-1.00
-3.21	-57.78	-1.75	-1.50
-4.83	-86.98	-2.50	-2.25
-6.10	-109.84	-2.75	-2.50
-8.43	-151.75	-3.50	-3.10
-10.41	-187.30	-4.00	-3.80
-12.38	-222.86	-4.50	-4.10

TABLE 2. Servo Stiffness Constant Data

LINEAR FORCE (oz)	LINEAR DEF (in)	TORQUE (oz-in)	SERVO DEF (deg)	TORQUE APPLIED TO BLADE (oz-in)	BLADE DEF (deg)
11.64	0.000	8.15	0.000	13.12	0.00
23.49	0.006	16.44	0.491	26.46	0.30
32.95	0.014	23.06	1.146	37.13	0.71
37.74	0.020	26.42	1.637	42.54	1.01
42.40	0.025	29.68	2.045	47.78	1.27
46.77	0.030	32.74	2.454	52.71	1.52

3. Rotating System Stiffness

Data obtained from the rotating system proved the system to be very "tight". Data can be seen in Table 3 and is plotted in Fig. 11.



Rotational System Stiffness
Constant
Figure 11

From the plot a stiffness coefficient of 128 oz-in/deg was obtained with a freeplay of approximately 0.2 degrees which is "very tight".

TABLE 3. Rotational System Stiffness Data

APPLIED FORCE (oz)	TORQUE (oz-in)	AVERAGE BLADE DEFLECTION (degrees)
0.56	10.16	0.250
2.33	41.90	0.500
7.44	133.97	1.238
12.56	226.03	1.825
16.26	292.70	2.500

4. Comparison of Theoretical and Experimentation

A quick and simple way to check the measured total system stiffness coefficient is by calculating a system stiffness through the use of the measured servo and rotating systems stiffness. Servo stiffness was multiplied by two since two servos act for any one movement of the swashplate. The following is a sample calculation:

$$K_{SYS} = \frac{K_{ROT} 2K_{SERVO}}{K_{ROT} + 2K_{SERVO}} \qquad \textbf{(16)}$$

$$K_{SYS} = 41 \; oz\text{-}inch/degree$$

This value of 41 oz-in/deg is within 30% of the measured stiffness of 56 oz-in/deg. The difference between measured and calculated stiffness can be attributed to a number of factors. Two major factors exist. First, as can be seen on all the stiffness graphs, the plots are not exactly linear. The total system and rotating system plot are nearly linear, but the servo plot shows a non-linear curve. This non-linearity can be attributed to the fact that the servos would actually bind and twist to some degree when load is applied. In addition, testing equipment was limited, so many measurements had to be made using simple unique and imaginative means. The final results show that the stiffness of the servos is too low to successfully handle HHC actuation. With this low of a stiffness, most of the HHC actuator output would be lost at the servo resulting in relatively no movement of the blade.

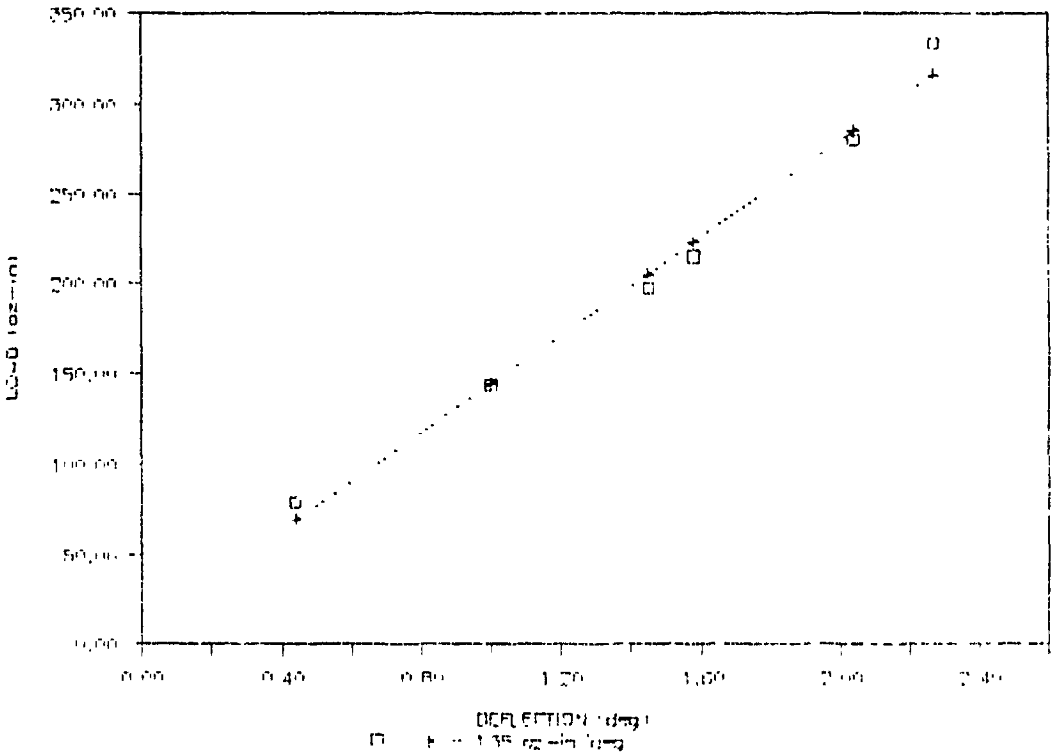
5. Blade Properties

Blade and associated equipment properties can be seen in Table 4 . The mass moments and weights were calculated.

Blade flapping hinge stiffness data is shown in Table 5 and plotted in Fig. 12. From the plot it is seen that the stiffness coefficient is 135 oz-in/deg with a freeplay of approximately 0.1 degrees. From these results it can be concluded that the blade flapping hinge is very stiff and should cause no problems with HHC actuation.

TABLE 4. Blade Mass Moments of Inertia

BLADE	BLADE GRIP	LOWER PITCH LINK	UPPER PITCH LINK	SYSTEM
.0075	.0007	.0008	.0006	.0096



Flap Hinge Stiffness Constant
FIGURE 12

TABLE 5. Flap Hinge Data

APPLIED FORCE (oz)	TORQUE (oz-in)	DEF AT DIAL INDICATOR (in)	FLAP ANGLE (degrees)
6.6	79.15	0.024	0.44
12.03	144.34	0.055	1.00
16.47	197.67	0.080	1.45
17.95	215.45	0.087	1.58
23.39	280.63	0.112	2.04
27.83	333.97	0.125	2.27

6. Power and Weight Requirements

With the knowledge of the system mass moment of inertia and the values obtained for maximum angular acceleration through the use of equations (12), (13) and (14), a maximum torque can be obtained through equation (15). At an omega of 502.7 rad/sec (80 Hz), and a blade angle of $\pm$ 1.0 degrees (0.0175 rad) this yields a maximum angular acceleration of 4422 rad/sec. Using this, a maximum torque of 42 oz-in is obtained from equation (15). This equates to an RMS torque of 30 oz-in.

The number calculated above is that of a system with no freeplay. If the system stiffness was brought up to that of the rotating system (128 oz-in/deg) there would be a deflection of .33 degrees at peak torque. This would result in a $\pm$ 1.33 degrees deflection that the motor must supply to provide an actual $\pm$ 1 degree movement in blade pitch. Using this figure for blade angle a new torque was calculated using equation (15). A new torque value was found to be 58 oz-in with an RMS value of 41 oz-in.

Since the actuators will have to perform both HHC and control system motion, power will be required in each individual actuator motor. Also power will be required for the HHC controller which is an addition to the RPH. The DC brushless motors chosen for this application will require 55 watts of power individually and the Vista HHC controller requires 20 watts. The total system power requirement comes to 240 watts. However, the existing electrical system only produces 3 watts of continuous power, far less than required.

With the additional power requirements comes weight. The RPH's useful payload is limited so weight has become a large factor. A simple breakdown of system component weights is as follows:

4 Motors = 4.6 lbs
4 Control Modules = .9 lbs
2 Batteries = 10 lbs
Vista Controller = 3 lbs
Misc = .75 lbs

As can be seen the system weight brings the RPH close to maximum gross weight.

7. System Frequency

The system frequency was calculated by using the projected system stiffness constant and mass moment of inertia in the following equation:

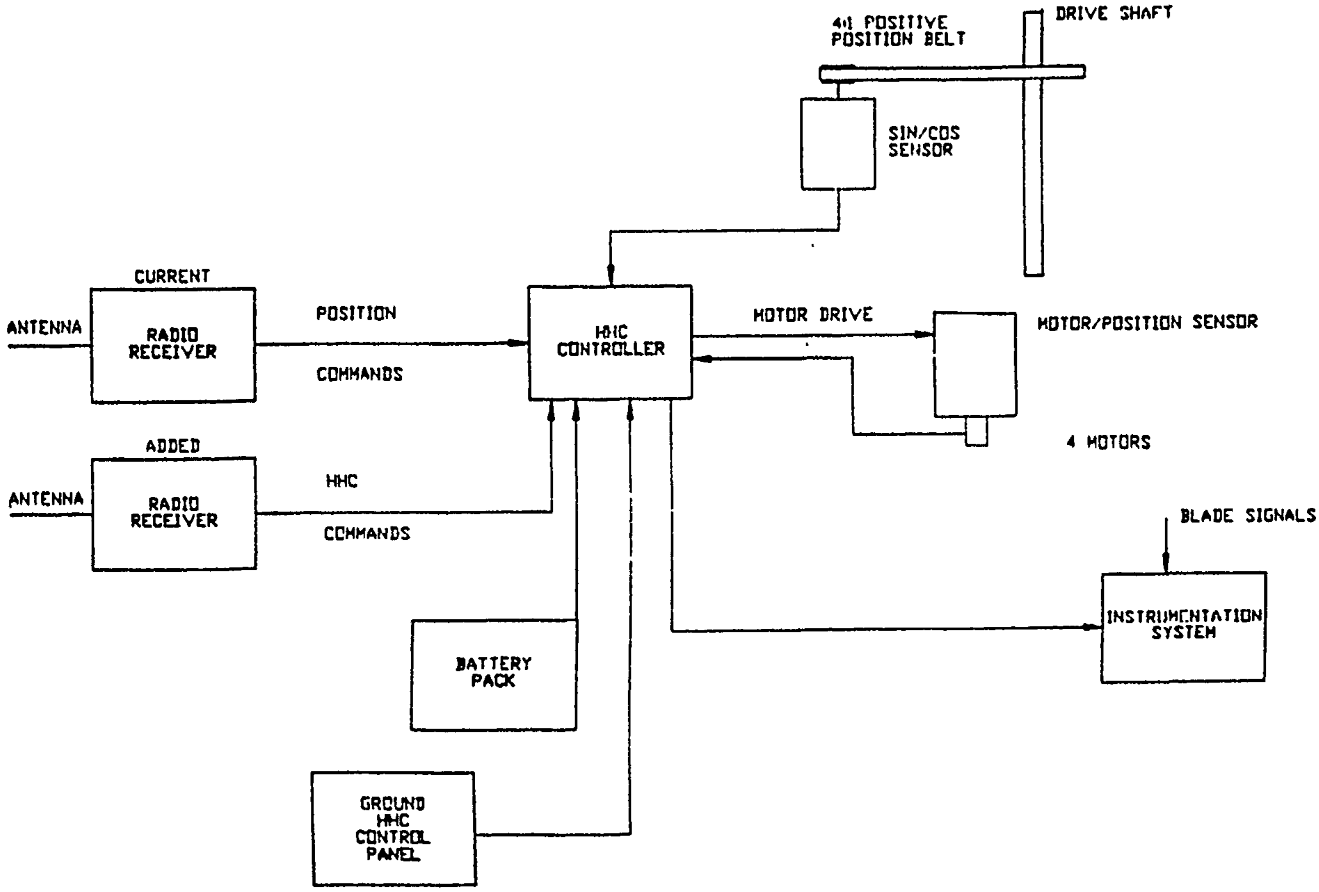
$$f_n = \left(\frac{K}{J}\right)^{\frac{1}{2}} \qquad (17)$$

The systems natural frequency using the projected stiffness is 113 Hz and the system actuation frequency is 80 Hz. It is a felt that this is enough separation to alleviate any problems with cross coupling.

8. HHC Electronics

An extensive modification of the flight control system will be required so that the 80 Hz HHC signal can be generated and used on the RPH, Fig 13. This new system will require the following changes and additions. 1) The radio receiver will be modified to include signals necessary for HHC. 2) New batteries will be added to supply the additional power requirement for HHC actuation. 3) A ground HHC control panel will be designed and fabricated for control of the HHC system during ground testing. 4) A sin/cos sensor will be added to the drive shaft to provide position/phase feedback to the HHC controller. 5) New servo motors and motor drivers will be added in place of existing servo motors. 6) A Vista controls digital controlled "Score Board" will be used for the HHC controller [Ref. 7].

With these modifications to the electrical and control system the RPH will have the capability of altering the phase and amplitude of the HHC signal.

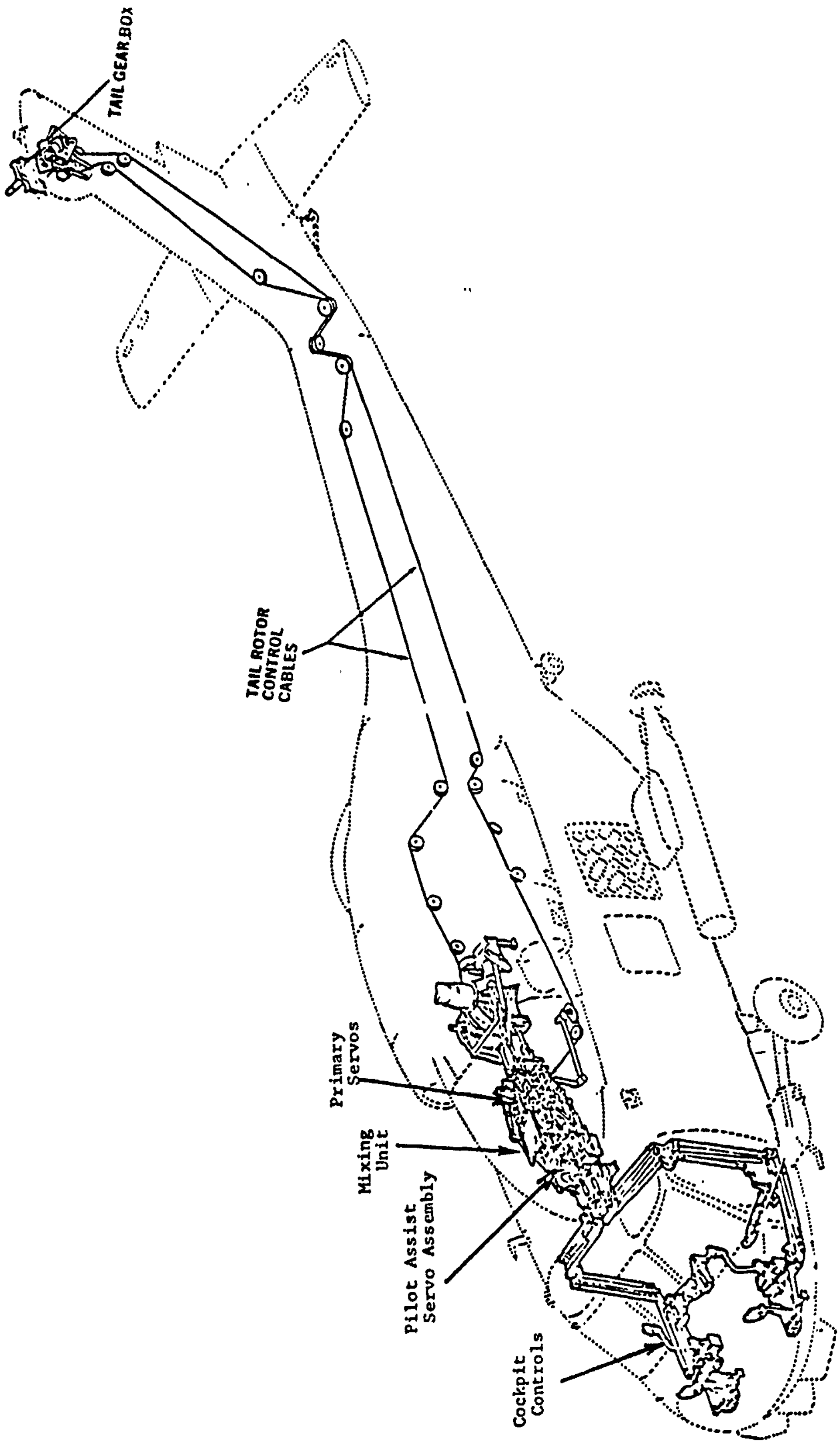


HHC System Block Diagram
Figure 13

V. SH-60B HHC PRACTICAL DESIGN CONSIDERATIONS

A. FLIGHT CONTROL SYSTEM DESCRIPTION

The platform that the Naval Air Test Center (NATC) would like to perform Higher Harmonic Control (HHC) on is the Navy's newest helicopter, the Sikorsky SH-60B. This aircraft possesses a conventional, mechanical, hydraulically boosted, irreversible flight control system which can be seen in Fig 14. This flight control system controls a four-bladed, fully articulated main rotor with a four-bladed canted tractor tail rotor with a fully controllable stabilator. The aircraft has duel controls so that the pilot and co-pilot have conventional control of the aircraft. Improved control characteristics and stability are provided by a digital automatic flight control system. The SH-60B was built with combat survivability in mind. All components are designed to be ballistically tolerant to a 7.62mm round. This ballistic tolerance is achieved through the following improvements: redundant cockpit controls, ballistically tolerant pushrods and pivots, ballistically tolerant servos, and redundant directional control quadrant. Combat survivability is also achieved by supplying hydraulic power to each servo stage from two independent sources with a backup from an emergency pump.

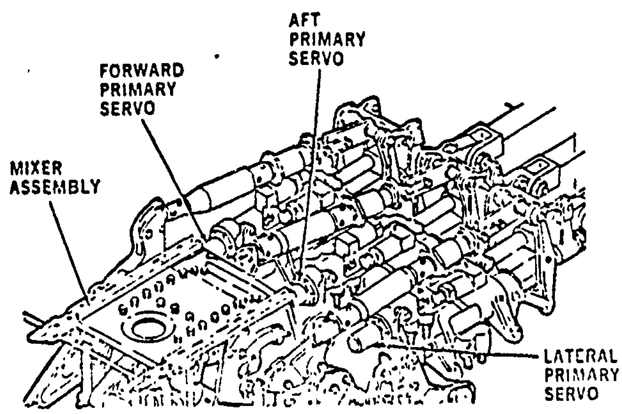


Flight Control System
Figure 14

1. Hydraulic System

The present hydraulic system contains three separate systems: The number one system provides 3050 $\pm$ 50 PSI through a pump mounted on and driven by the left accessory module of the main transmission. The number two hydraulic system provides 3050 $\pm$ 50 PSI through a pump mounted on and driven by the right accessory module of the main transmission. The backup/emergency hydraulic system is powered by an A.C. electric motor which drives the hydraulic pump. This system will provide hydraulic pressure to the second stage of the tail rotor servo and to the number one and/or the number two system if hydraulic pressure drops [Ref. 8].

The hydraulic system contains three types of servos: primary, tail rotor and pilot assist. There are three main rotor dual hydraulic primary servos that are located on the main gear box, Fig 15. The servos provide the necessary boost required to move the main rotor controls. In the event of an inoperative leaking servo a shut off system has been incorporated to maintain overall system pressure. Also if a stage becomes inoperable an internal bypass valve will open to relieve pressure so that a hydraulic lock can be prevented. One tail rotor servo is mounted on the tail rotor gearbox and is seen in Fig 16. To provide redundant directional control the servo contains two stages. Stages 1 and 2 are powered by the No. 1 hydraulic system and back-up system respectively. If one fails the other takes up the load. The pilot assist servos are many and consist of the following: collective yaw and pitch boost servos, pitch, roll and yaw stability augmentation system (SAS) actuators and the collective inner loop actuator. The servos are powered by the number two system and the backup. The boost servos are used to



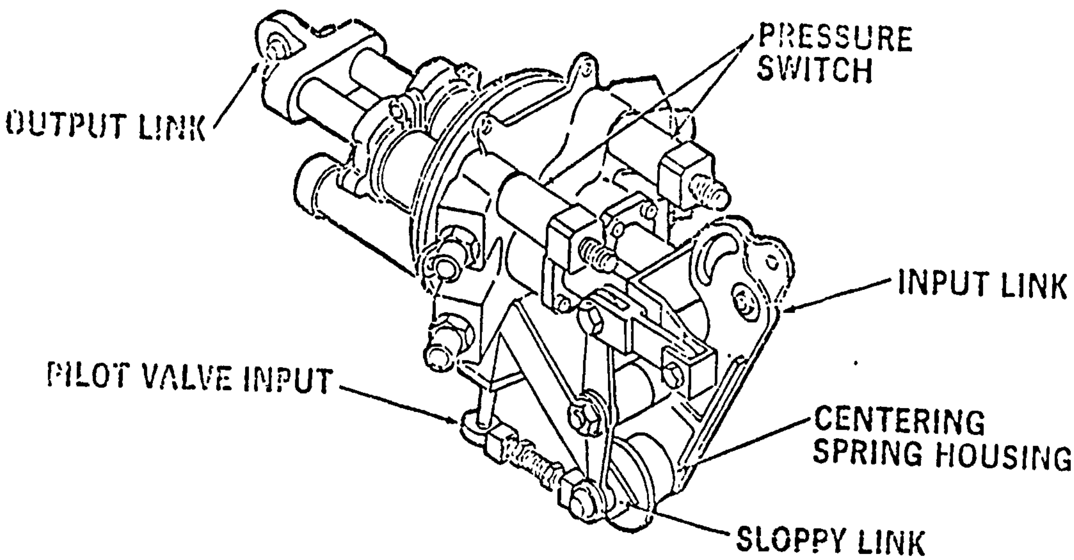
Primary Servos
Figure 15

reduce cockpit control forces and SAS system feedback. The SAS actuators and the collective inner loop actuator are used to transfer output from the SAS controllers and Electronic Flight Control System (EFCS) into flight control actuation [Ref. 8].

2. Flight Controls

a. Cyclic Control System

Longitudinal and lateral control of the helicopter are achieved by tilting the tip path plane of the main rotor disk. To achieve this, inputs into the longitudinal and lateral system are transmitted via cyclic sticks, control rods and bellcranks via control rods into



Tail Rotor Servo
Figure 16

the pilot assist servos which incorporate trim inputs. The longitudinal input is boosted by the pitch boost servo with both longitudinal and lateral SAS actuators providing inputs. The longitudinal input then travels to the pitch bias actuator then on to the mixing unit while the lateral input travels to the mixing unit. From the mixing unit the inputs travel via control rods to the forward and aft primary servos for the longitudinal and the lateral primary servo for the lateral input. The inputs are carried from the servos to the stationary swash plate via control rods and bellcranks. There control links move the stationary swashplate to provide longitudinal and lateral movement of the rotor disk.

b. Collective Control System

Vertical control of the aircraft is achieved by collectively changing the pitch of the main rotor blades. The collective input is transmitted through the pilot's and co-pilot's collective pitch levers then through linkages up to torque tubes. Trim inputs are made at this point and then the input is transmitted back to the collective boost servo and collective inner loop actuator where inputs are applied based upon EFCS signals. From here the input is transmitted to the mixing unit where the collective input is mechanically mixed with all other controls causing output to the tail rotor and to all three primary servos.

c. Directional Control System

Directional control of the aircraft is achieved by collectively varying the pitch of tail rotor blades so that the torque of the main rotor can be counteracted. Directional inputs are made through the pilot and co-pilot directional pedals and are transmitted from there in the same manner as the other controls, through the pilot assist servo assembly. Located on the tailrotor gearbox is the tail rotor quadrant which transmits tail rotor cable movement to the tail rotor servo which moves the pitch change shaft. The quadrant contains two springs which are designed to let the quadrant control the tail rotor in the direction of a cable failure. Finally the pitch of the blades is controlled by the pitch shaft which extends through the gearbox and moves the pitch change beam attached to the blade.

d. Mixing Unit

All control inputs are mechanically mixed through the mixing unit. In other words, when collective is increased tail rotor pitch is increased to compensate. The effect of rotor downwash on the stabilator is countered by collective to longitudinal mixing. Collective to roll mixing is used to counter right roll when collective is increased. Many other control mixing variations are performed and after they are mixed the output is transmitted to the three primary servos and tail rotor forward quadrant.

VI. HYDRAULIC/MECHANICAL DESIGN

A. OBJECTIVES

To achieve a working HHC design which will provide the desired effects at a minimum cost the following objectives should be set. 1) HHC blade feathering should be provided by some type or electro-hydraulic actuator. For the SH-60B this type of actuator should be able to provide a continuous output at 4/rev or 17.2 Hz. 2) By locating the HHC actuators in the non-rotating system, generation of multiple frequencies (3P, 4P and 5P) is not required as would be in the rotating system. By proper phasing of the 4P any combination of blade 3 , 4P and 5P feathering can be generated. Other advantages are that there is no need for a hydraulic manifold and slip ring assembly and the actuators and tubing will not have to operate in a centrifugal force field. 3) To maintain simplicity the system should be designed to meet one goal, minimizing 4P rotor forces feeding into the fuselage. Due to possible funding constraints the simple objective of minimizing 4P forces will reduce cost design and implementation time. 4) Limit the system weight penalty to less than 2% design gross weight. 5) Higher Harmonic Control signals should be superimposed on the primary controls so as to minimize effects on rotor trim. In all the HHC designs to be presented, the HHC signal is meant to be superimposed upon the primary control system. By superimposing the HHC signal on the primary control, a safety feature is built into the system. If HHC fails or has a malfunction, the control system can revert back to the primary system. By using the superimposed system HHC can be implemented in several ways: different actuators or integrated [Ref. 9].

B. MECHANICAL DESIGN

Four approaches to HHC power and mechanization are to be studied in the following pages. The four approaches will provide for different actuators, actuator locations and controls. The four different concepts are as follows:

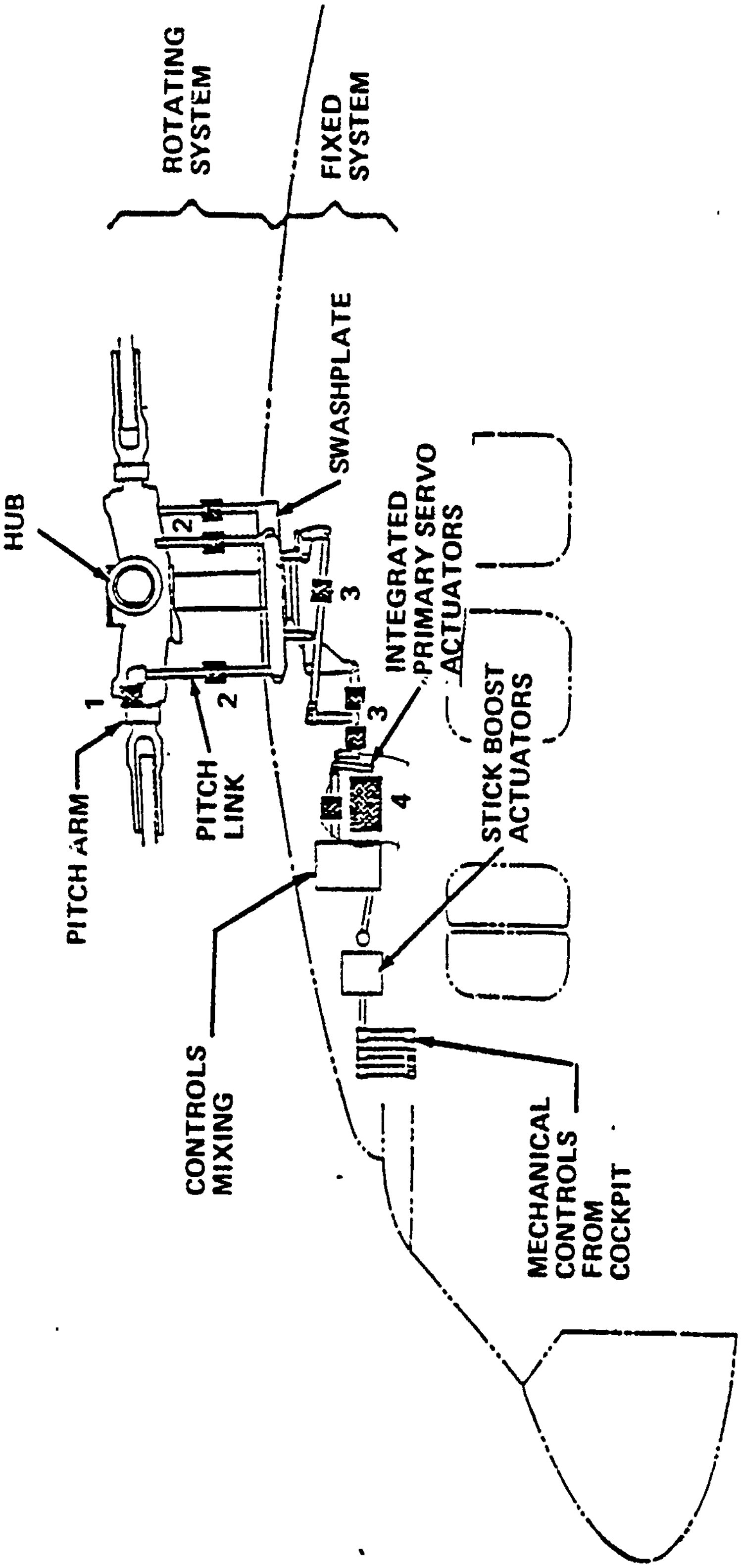
1. Pitch arm actuation/pitch link actuation
2. Linkages above primary servo
3. Integrated primary servo
4. Lower control linkage

The lower control linkage is deleted because it will need new driver actuators as well as primary servos. Also the pitch arm actuation concept is deleted because it shows no substantial advantages over the pitch link actuation and promise to be much more complex.

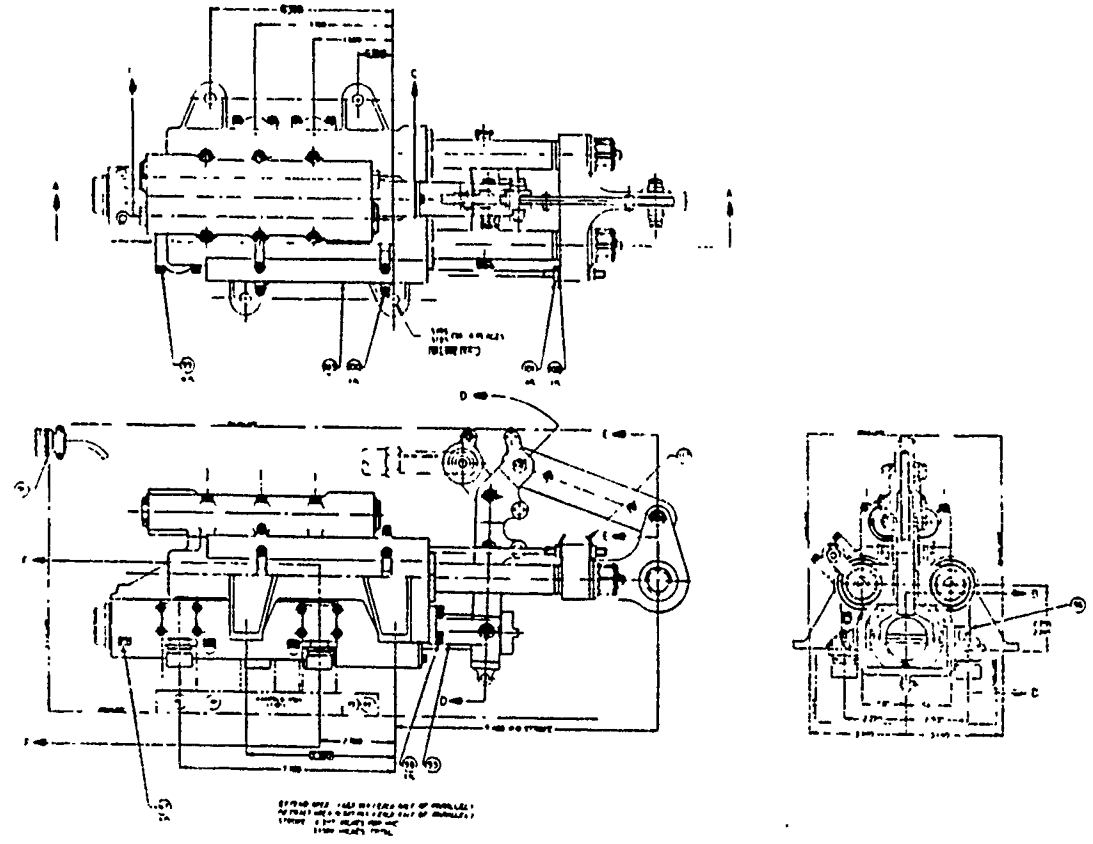
The first HHC mechanical design concept is that of a series HHC actuator in the rotating system. With this type of actuator assembly a few unique components would be required. To power the actuators a rotating hydraulic manifold and a slip ring assembly will be needed to transfer the hydraulic power from the stationary system to the rotating system. This would require major modification to the existing hydraulic system. This component alone could limit the use of this type of design. Fig 17 shows the proposed location of the series HHC actuator. Another disadvantage to this design is that it is in the rotating system and with the addition to added weight on the pitch arm/link assemblies all related components would have to be strengthened to take the centrifugal loads created by this new weight.

The second approach to HHC power and mechanization is that of a series HHC actuator in the fixed system location seen in Fig 17. With this design the normal control sequence is carried out by the control system but an HHC signal is superimposed on the system by means of an electro-hydraulic servo producing HHC inputs. In case of problems with the HHC signal in flight some type of lockout device or failsafe actuator will be required. This failsafe actuator or locked device should provide positive piston body locking so that normal control can be maintained. Even though space is at a premium this design could possible be placed in two different locations as seen in Fig 17. The actuators should be placed after the control mixing unit as shown in Fig 17. The HHC control load will not be felt by the pilot but instead will be transmitted to the rotor. If particular attention is paid to the stiffness of the system this design should show good 4P frequency response. Disadvantages to this design would be that some control components may need redesigning so that they could take the higher HHC loads. Space will be at a premium and the hydraulic system will need modifications.

The third and final concept design would be that of a dual integrated primary servo, Fig 18. This design concept could replace the existing primary servo actuator and be located in the same vicinity. By replacing the existing primary servo with a dual integrated servo a small weight savings may be gained. By the use of an integrated servo the functions of primary control boost and 4P control feathering can be combined into one unit.



Actuation Candidate Concepts
Figure 17



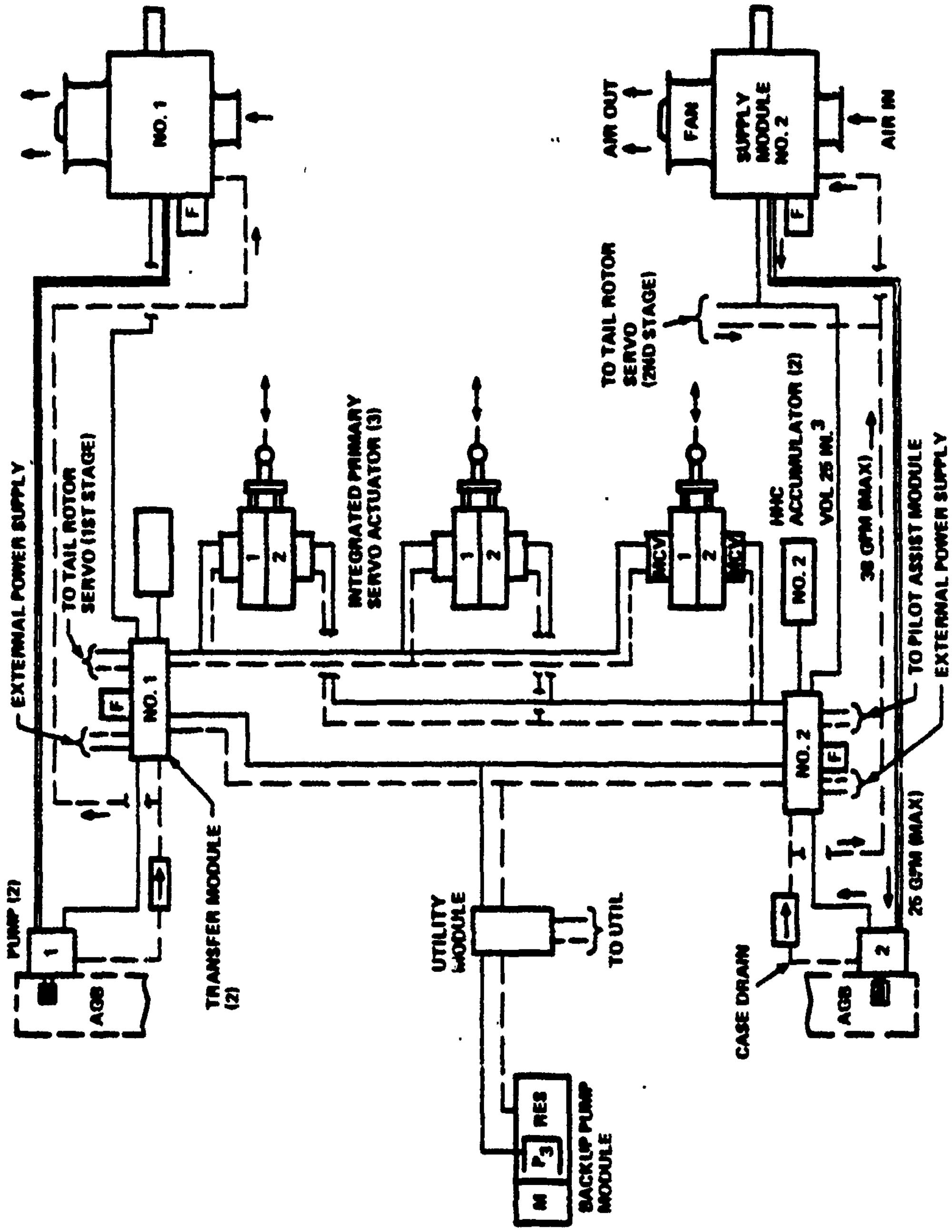
Dual Integrated Primary Servo
Figure 18

A dual integrated primary servo will not require a center/lock mechanism for HHC shutdown and no emergency lock pressure supply will be required. This concept will also require the least amount of modification to the existing hydraulic systems. With this design a good 4P frequency response should be achieved since it will also be located after the mixer, Fig 17. Disadvantages to this design concept was that it will require a redesign of the primary servo actuator.

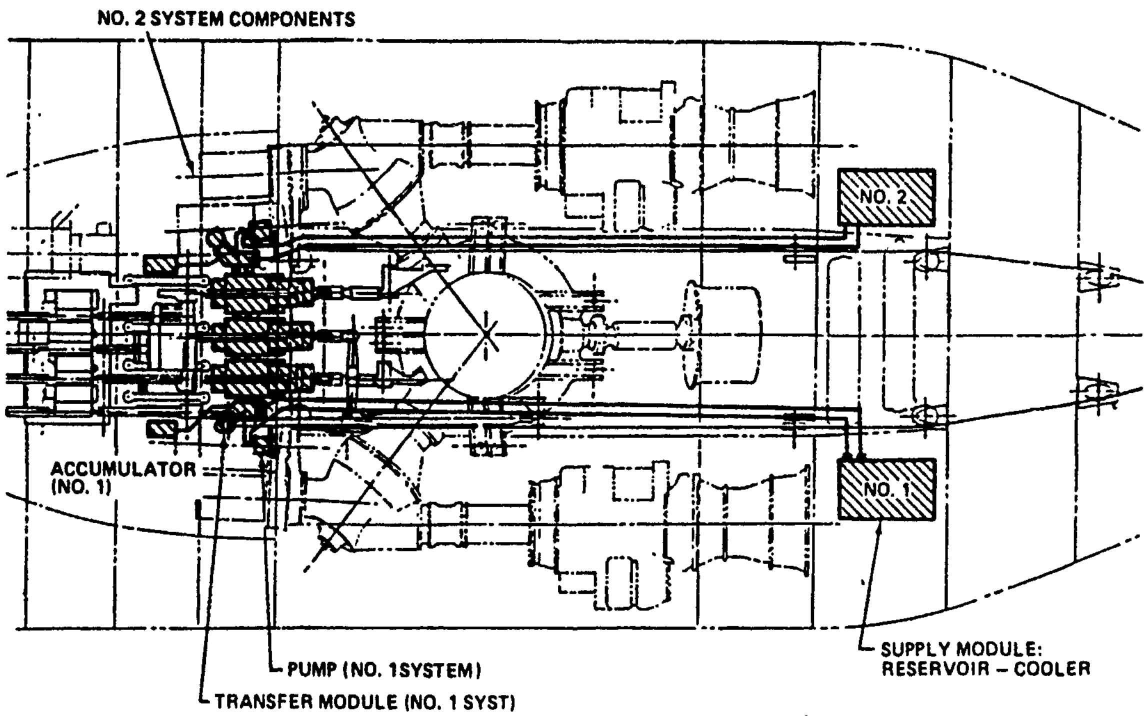
By placing these systems after the mixer assembly HHC feedback should be redirected by mixer cross-coupling and should not be felt in the lower controls. Also feedback should be present in the collective and yaw control paths by lower control boost actuators but if it does reach the pilot's stick through pitch and roll changes, small control link dampers might need to be installed.

C. HYDRAULICS

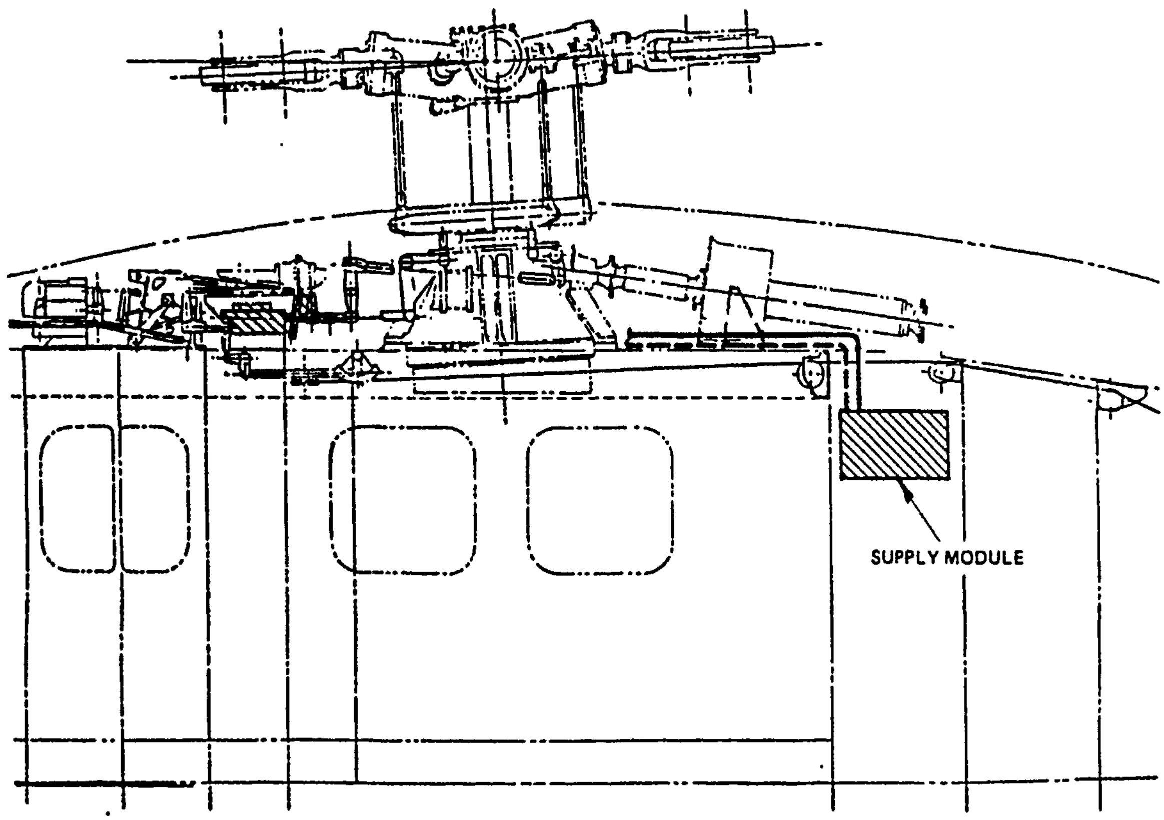
With the addition of any one of the three actuator designs an associated modification of the existing hydraulic system will be required. At present the hydraulic system provide 3050 $\pm$ 50 PSI with a pumping capacity of 6 GPM. Also the present system contains no endogenous hydraulic cooling system. All three designs should work with the 3050 PSI system but will require much higher pumping capacities and cooling capacities. By replacing the existing pumps with higher output pumps and locating larger hydraulic reservoir/coolers aft and below the engines the system should be easily modified to supply the necessary pumping capabilities along with the necessary cooling capacities. This design can be seen in Fig 19 and its location is shown in Figs 20 and 21 [Ref. 10].



GENERAL ARRANGEMENT
FIGURE 19



HYDRAULIC COMPONENT ARRANGEMENT
FIGURE 20



HYDRAULIC COMPONENT ARRANGEMENT
FIGURE 21

VII. CONCLUSIONS AND RECOMMENDATIONS

A. RPH CONCLUSIONS

This project is one in which a multitude of students will be able to gain valuable research on helicopter Higher Harmonic Control. The goal of this thesis work was to determine if the existing RPH flight control system could be used for HHC flight or if it would have to be modified. After the completion of this work the HHC RPH work has been split into five projects for follow-on students. The five projects consist of: 1) actuator redesign and implementation 2) actuator controller design 3) instrumentation implementation 4) control law formulation and 5) system integration.

Upon completion of this study it was noted that the existing flight control system is incapable of achieving the requirements needed for HHC actuation. The initial check of the total system stiffness constant showed that the present system did not contain the stiffness required to have a working HHC actuation system. Follow on tests found that the servo linkages were the weak point and the rotating system was the strong point of the system. At this point it was felt that the total system could be brought up to the stiffness coefficient for the rotating system by replacing the existing actuators and the plastic linkages with aluminum linkages using the projected system stiffness. As seen in the results section the present RPH is grossly underpowered electrically for HHC implementation. To achieve the power requirement for HHC actuation two of the off-the-shelf batteries can be used to supply power required. It must be remembered that the

HHC can only be run for short periods so as not to drain the batteries, losing electrical power and ultimately the aircraft. Once the next step of implementing new actuator and linkages is completed, a new study of stiffness freeplay and power requirements can be calculated to check that the new system is appropriate for HHC actuation.

B. RPH RECOMMENDATIONS

After completion of this study, it is clearly seen that this on-going research in HHC should be continued. A good rapport has been built with Vista Controls and the student-contractor projects should be the next work completed. Upon completion of the student-contractor work a committee of students, contractor personnel and faculty should perform a safety of flight review prior to the first ground test. In conjunction with the last phase of student contractor work and during the safety of flight review a student project of the designing and implementing a data recording system along with a test plan i.e., ground test, hover and forward flight. Another area that student work will help with further HHC development is that of modeling the RPH on MSC XL and analysis on MSC NASTRAN soon to be available at NPS.

This project should not be rushed in any way but should proceed on a planned and methodical course. There is presently enough material here for eight to ten students to get the RPH in the air with HHC.

C. SH-60B CONCLUSIONS

The SH-60B will prove to be a viable platform for the implementation of Higher Harmonic Control. This study has given examples of three types of actuation systems that might prove to be workable solutions. The dual integration servo actuator may prove to be the best candidate for this aircraft. By using this actuator only a simple change out of the existing primary servo is needed. No extra linkages or extra servo actuators will be required to be placed in the mechanical system. Also this will call for the least amount of design and redesign effort. It was noted that with all three designs the hydraulics system would require modifications; the two stationary designs would require far less modification, thus proving to be less costly. The series HHC actuator would require extra linkages and another servo actuator plus a system by which it could be locked out in times of emergency. All of this means added weight, space and cost. The choice here would be four dual integrated primary servo actuators.

D. SH-60B RECOMMENDATIONS

A much more detailed study should be performed to produce detailed engineering drawings, loadings and power requirements for the HHC actuators. With this study actuator designs can be produced and built or off-the-shelf actuators can be purchased and tested.

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